Journal of Rock Mechanics and Geotechnical Engineering. 2009, 1 (1): 48–55

CSRME

Journal of Rock Mechanics and Geotechnical Engineering

Journal online: www.rockgeotech.org

Controlling strain in geosynthetic liner systems used in vertically expanded landfills

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Received 12 February 2009; received in revised form 10 August 2009; accepted 28 August 2009

Abstract: According to relevant new regulations in China, a composite liner system involving geosynthetic materials must be installed at the bottom of an expanded landfill. The deformation and integrity of the composite liner under a variety of factors are important issue to be considered in the design of a landfill expansion. In this paper, we investigate the strain distribution in geosynthetic materials within the composite liner system of expanded landfills, including strains in geosynthetic materials resulting from overall settlement and lateral movement of landfills, localized subsidence in landfills, and differential settlement around gas venting wells. The allowable strains of geosynthetic materials are discussed based on the results of tensile tests, and the corresponding design criteria for composite liner systems are proposed. Meanwhile, practical measures allowing strain control in geosynthetic materials used in landfill engineering are proposed.

Key words: landfill; composite liner system; geosynthetics; strain

1 Introduction

Significant growth in the population and economy of most urban areas of China since the 1990s has resulted in a rapid increase in the generation of municipal solid waste (MSW). About 90% of these highly compressible materials are disposed of in landfills. However, most of the landfills in major cities were built in the early 1990s and have now reached their designed service lifespan [1]. Expansion of these landfills is hampered because many of the earlier-constructed landfills were not appropriately lined with clay liners or geomembranes (GMs). According to new Chinese regulations [2], expanded landfills must incorporate a composite liner system using geosynthetic materials.

The expansion of existing landfills is currently underway in many cities of China due to difficulties in obtaining new landfill sites. However, the addition of waste through vertical landfill expansions will cause overall settlement and lateral movement in the underlying older landfill, which could strain geosynthetic materials in a composite liner system and alter the inclination of the leachate drainage layer. Voids (holes or cavings) or local subsidence are often caused by progressive degradation and collapse of large-sized objects buried in existing landfills. Such voids can cause "localized" deformations and strains in geosynthetic materials in the composite liner systems. In addition, GMs in composite liner systems are often connected to rigid circular structures (e.g. gas venting wells in the existing landfills). GMs can exhibit excessive tensions and strains in the areas connected to such rigid structures due to differential settlement [3]. Thus, the serviceability and structural integrity of geosynthetic materials in composite liner systems subjected to differential settlements are important design consideration for landfill expansion. If the induced tensile strain in the geosynthetic material exceeds the tensile strength of the sealing material, tensile failure (e.g. cracking) will occur and the effectiveness of the liner as a hydraulic barrier will be compromised because such cracks may provide direct flow pathways through the composite liner system [4].

This paper investigates strain within geosynthetic materials in the composite liner systems of expanded landfills, including strain resulting from the overall settlement and lateral movement of existing landfills, local subsidence and differential settlement around gas venting wells. The allowable strains of the geosynthetic materials are discussed based on the results of tensile tests, and a design criterion is proposed. Finally, practical recommendations are proposed for controlling

Doi: 10.3724/SP.J.1235.2009.00048
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Supported by the National Natural Science Foundation of China (50538080)

tensile strains in geosynthetic materials for landfill engineering.

2 Analysis of strain in geosynthetic materials

The Suzhou landfill near Shanghai was commissioned in 1993. It is located in a valley surrounded by hills, about 13 km from Suzhou City. The landfill has reached its maximum design level by the end of 2008. Designs for vertical and lateral expansions of the existing landfill are underway. The preliminary design involves the vertical expansion of the existing landfill from 80 to 120 m, and an outward expansion of 400 m from the present landfill boundaries, as illustrated in Fig.1.

The bottom of the existing landfill was not lined with any form of engineering barrier when it was constructed. An injected grouted curtain was installed under the retaining wall of the leachate pond to limit downstream leachate movements. The grouted curtain extended to the underlying fresh rock which had a high structural integrity and a permeability less than 1×10^{-9} m/s. The grouted curtain and the fresh rock were expected to constitute a closed barrier system against leachate movement in the existing landfill. However, monitoring of the downstream flow of groundwater in the grouted curtain indicated that the barrier system did not perform as expected. In accordance with the new regulation, the bottom of the expanded waste body will be lined with a composite liner system.

2.1 Overall settlement and lateral movement in existing landfill

The assessment of strain in potential geosynthetic materials requires not only a reliable estimate of the overall deformation in an existing landfill but also an understanding of the interactions between a new liner system and the old underlying landfill material. This is a challenging problem. Qian et al. [5] presented a simple equation for the rough estimation of strain in geosynthetic materials subjected to overall settlement. The equation is based on the assumptions that the landfill has negligible lateral movement and that no slippage occurs at the interface between the liner system and the waste body. The strain in the geosynthetic material of the composite liner system can be evaluated by observing progressive changes in selected cross-sections through the existing landfill and comparing the pre- and post-settlement liner configurations (Fig.2). It should be noted that the magnitudes of strain for the geosynthetic materials may be significantly underestimated by this method. An existing landfill sitting on sloping ground usually undergoes some lateral movement during vertical expansion (Fig.3). Thus, the composite liner system will also be subjected to lateral movement, leading to deformation and strain accumulation.

To predict the settlement behavior of the Suzhou landfill, samples were taken at boreholes with a range of depths [6]. The samples were tested in the laboratory with primary compressions.

For the purpose of illustration, a cross-section with a horizontal length of 200 m was chosen for the settlement analyses (Fig.1). Due to the absence of reliable parameters for describing the time-dependent compression behavior of the waste layers, only the primary settlement due to the incremental load of the expanded fill was calculated using the experimental values of the primary compression index (C_c). Figure 4 shows the calculated primary settlement of the existing landfill and induced tensile strain in the geosynthetic materials. The incremental load of the expanded landfill can result in a maximum settlement of about 3.9 m. The maximum tensile strain ε_{max} in the geosynthetic materials estimated by the equation presented by Qian et al. [5] is only 0.8%.

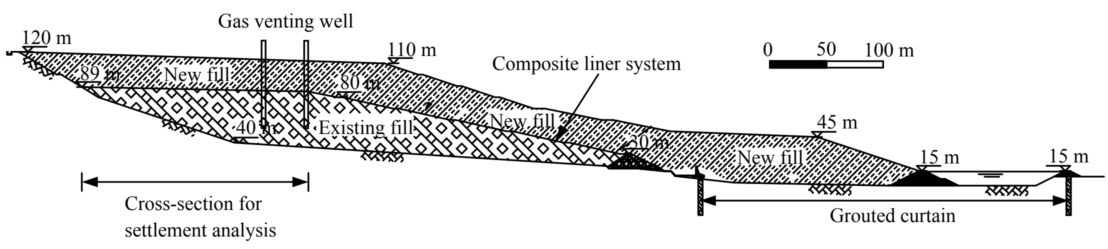

Fig.1 A preliminary design of expansion in Suzhou landfill.

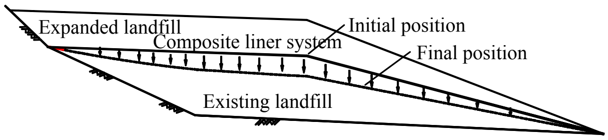

Fig.2 Overall settlement of existing landfill.

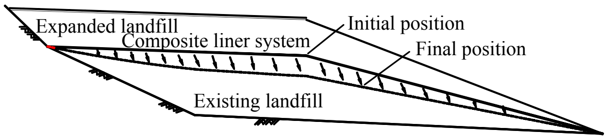

Fig.3 Overall settlement and lateral movement of existing landfill.

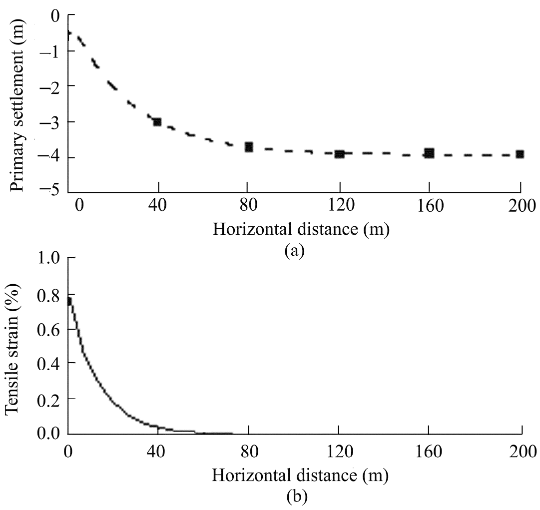

Fig.4 Primary settlement of the existing landfill and induced tensile strain in the geosynthetic material.

At present, no analytical or empirical method has been established for evaluating the lateral movement of a landfill. However, numerical modeling can be adopted to solve this two-dimensional (2D) problem, in which the constitutive model for MSW is important.

A composite exponential model for MSW was proposed based on large-scale triaxial shearing test results by Chen et al. [7]. The expressions of the model are

$$\sigma_1 - \sigma_3 = \left[k_1 P_a \left(\frac{\sigma_3}{P_a} \right)^{n_1} \varepsilon_a + k_c \sigma_3 \right] \left\{ 1 - e^{-\left[\frac{k_2}{k_c} \left(\frac{\sigma_3}{P_a} \right)^{n_2 - 1} \right] \varepsilon_a} \right\} \tag{1}$$

$$\nu = \min\{0.3 + k_\nu (\sigma_3 / P_a),\ 0.45\} \tag{2}$$

where $\sigma_1 - \sigma_3$ is the deviatoric stress, ν is the Poisson's ratio, P_a is the atmospheric air pressure (P_a=101.3 kPa), and k_1, n_1, k_2, n_2, k_c, k_ν are all experimental constants. This constitutive model for MSW has been incorporated into a computer code FLAC, which is capable of numerically modeling deformation due to gravitational forces. In this model, the time-dependent degradation of MSW is not taken into account.

The code FLAC with the composite exponential model was adopted to analyze the potential strains of the geosynthetic materials in the composite liner systems that were induced by the overall settlement and lateral movement of the existing landfill. The parameters for the composite exponential model of MSW are shown in Table 1. The composite liner system was modeled by beam elements without bending resistance. The main part of the Suzhou landfill was taken into consideration in the analysis. Figure 5 shows the calculated results. It can be seen that the maximum lateral movement of the existing landfill is 2.44 m, which happens at the front of the slope, and the maximum settlement is 4.55 m.

Table 1 Parameters for composite exponential model.

k_1	n_1	k_c	k_2	n_2	k_ν
15.022	0.404	0.368	76.033	0.428	0.031 4

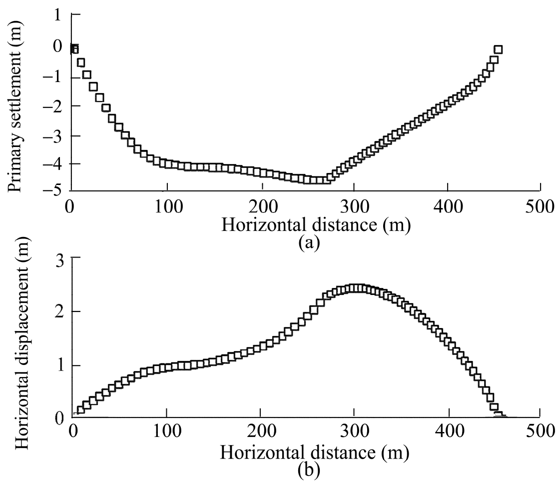

Fig.5 Settlement and horizontal displacement of the surface of the existing landfill.

Figures 6 and 7 show the displacement vectors of the composite liner system and the horizontal distribution of strains in the geosynthetic materials, respectively. The maximum tensile strain ε_{max} in the geosynthetics is 2.06%, which appears near the anchor trench on the back slope of the existing landfill. It is interesting that compressive strains (negative values) occur on the front slope of the existing landfill, which means that the liner system in this location will relax. The lateral movement of the existing landfill will have an apparent effect on the magnitudes and distribution of strains in the geosynthetic materials at local positions. Further theoretical and experimental studies involving

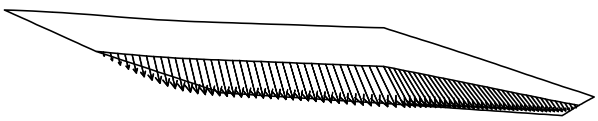

Fig.6 Displacement vectors of composite liner system.

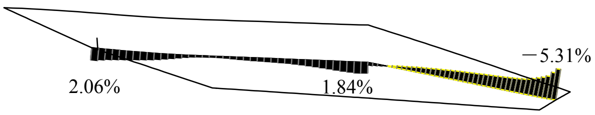

Fig.7 Strain horizontal distribution of geosynthetic material.

time-dependent degradation of MSW are required for an improved understanding on this problem.

2.2 Local subsidence in an existing landfill

As stated before, voids or local subsidence within the existing landfill may occur because of the collapse or degradation of large-size objects in the MSW. At present, it is common engineering practice to reinforce composite liner system with geogrids or high strength geotextiles to accommodate subsidence effects. The current state-of-the-practice is to design for a void of 1.8–2.4 m in diameter (the so-called "refrigerator effect"). The design of the geosynthetic reinforcement is based on a worst-case scenario with the assumption that a void is located immediately underneath the liner. The liner is then treated as a plate bridging the void and carrying the load of the proposed overlying waste (Fig.8).

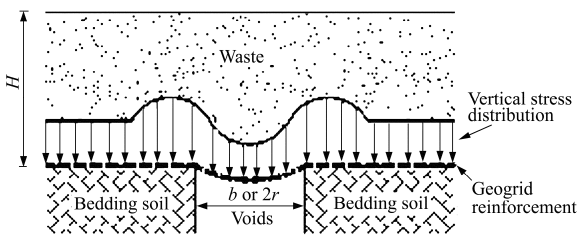

Fig.8 Geosynthetic reinforcement landfill voids.

The design method has been developed using arching theory and tensioned membrane theory [8]. The calculation formulas are expressed as

$$p = \frac{\gamma r}{2K\tan\phi}[1 - \mathrm{e}^{-2K\tan\phi(H/r)}] \tag{3}$$

$$T_r = pr\Omega \tag{4}$$

$$\Omega = 0.25\left(\frac{y}{r} + \frac{r}{y}\right) \tag{5}$$

where p is the normal pressure acting on the reinforcement over the void, T_r is the tensile load of reinforcement, γ is the unit weight of waste contained above the lining system, K is the coefficient lateral earth pressure coefficient, ϕ is the friction angle of waste, H is the thickness of waste contained above the lining system, r is the radius of the void, and Ω is the dimensionless factor related to reinforcement deflection y or strain ε.

Equations (3) and (4) are also valid for long voids where r is replaced by a width of void b, while r is replaced by $b/2$ in Eq.(5). Since the stress state of the soil in the arching zone is not fully understood at present, various values of the lateral earth pressure coefficient K have been adopted. Terzaghi [9] referred to K as "an empirical coefficient", while Giroud et al. [8] and McKelvey [10] preferred the use of Handy coefficient [11] in the expression of Terzaghi loosen earth pressure (Eq.(3)), which is defined as

$$K = 1.06(\cos^2\theta + K_\mathrm{a}\sin^2\theta) \tag{6}$$

where $\theta = 45° + \phi/2$. Recently, the authors proposed a modified lateral earth pressure coefficient K' considering rotations of principal stress axes of soil in the arching zone, and its expression is

$$K' = \frac{\cos^2\theta + K_\mathrm{p}\sin^2\theta}{\sin^2\theta + K_\mathrm{p}\cos^2\theta} \tag{7}$$

where K_p is the Rankine passive earth pressure coefficient. Calculated values of K' vary between 1.43 and 2.41 for a range of friction angle from 25° to 40°. Figure 9 shows the normal pressures on the trapdoor, calculated by the present lateral earth pressure coefficient and some other available ones. It can be found that the present result is in the best agreement with the tested result of Adachi et al. [12] compared with other coefficients.

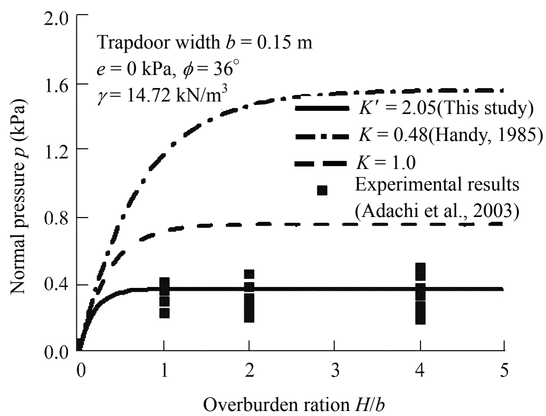

Fig.9 Comparison of calculated normal pressures.

A default assumption in the method of Giroud et al. [9] is that the soil deformation required for arch generation is compatible with the tensile strain required to mobilize tension in the geosynthetic materials. However, it is possible that the degree of the soil arching depends on the deflection of the geosynthetic liner. In an idealized case in which the geosynthetic reinforcement is perfectly rigid, there is no deflection that leads to stretching of the reinforcement. As such, there will be no soil arching or tensioned membrane effects. In this paper, the vertical earth pressure acting on the geosynthetic liner, which is related to the vertical displacement of the geosynthetic liner, is given as

$$p(y) = (\gamma H - p_0)\mathrm{e}^{-\frac{yE\lambda}{r\gamma H}} + p_0 \tag{8}$$

where the normal pressure p_0 is calculated by Eq.(3) using the modified lateral earth pressure coefficient K', λ is a dimensionless factor and is suggested to be 1.76, E is the elastic modulus of the waste. For long voids, r can be replaced by the width b in Eq.(8). Figure 10 shows the effect of the normalized geosynthetic liner deflection ($y/(2r)$) on the load ratio ($p/(\gamma H)$). Clearly, $p(y)$ is equal to γH when y is zero, which means that there is no soil arching effect. The value of $p(y)$ will approach p_0 when the geosynthetic liner deflection y is large enough. Parametric studies also show that with an increase of the waste thickness (H), a larger geosynthetic liner deflection is needed to reach the full degree of soil arching (see Fig.11).

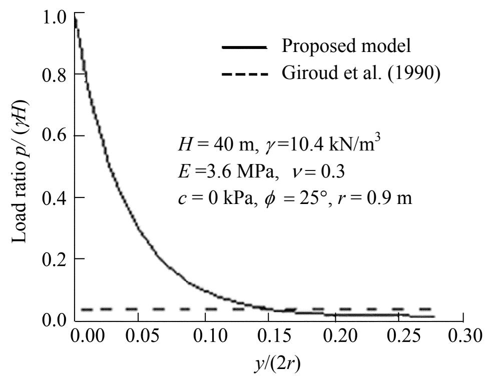

Fig.10 Effect of geosynthetic liner deflection on load ratio.

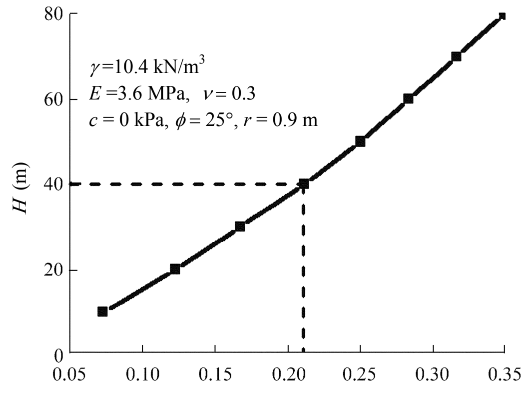

Fig.11 Relationship between waste thickness H and geosynthetic liner deflection needed to reach full degree of soil arching.

Figure 12 shows the calculated tensile load of the geosynthetic reinforcement using the present method and that presented by Giroud et al. [8]. The radius of the void is selected to be 0.9 m. The allowable design strain ε is considered to be 7%. For $\varepsilon = 7\%$, $\Omega = 0.84$ and $y/(2r) = 0.164$ according to Giroud et al. [8]. Thus, the normal pressure $p(y)$ in Eq.(8) and tensile load T_r in Eq.(4) can be determined. The method presented by Giroud et al. [8] is conservative when the overlying waste thickness is less than about 42 m. However, it will significantly underestimate the value of T_r when the overlying waste thickness is larger than 42 m. This is because that the method in Giroud et al. [8] cannot consider the displacement-related vertical earth pressure, and it underestimates this value when a large overlying waste thickness is needed. For the Suzhou expanded landfill (H = 40 m), the calculated tensile load in the geosynthetic liner is 12.2 kN/m by the method of Giroud et al. [8]. Considering the reduction factor RF_{CR} accounting for creep of geosynthetic liner (RF_{CR} = 2.5), RF_{ID} accounting for installation damage (RF_{ID} = 1.5), and RF_{CBD} accounting for chemical and biological degradation (RF_{CBD} = 1.2), the long-term allowable design tensile load is 54.9 kN/m. If the considered void radius is 1.2 m, the value will be about 100 kN/m. Therefore, two layers of the geogrids with high strength would be needed to satisfy the design requirement.

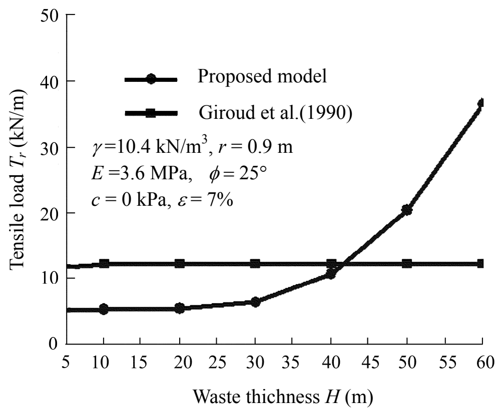

Fig.12 Comparison of tensile load of geosynthetic liner calculated by different methods.

2.3 Differential settlement around gas venting wells

When vertical gas venting wells are constructed in a landfill expansion, the integrity of the GM in the composite liner system connected with the rigid well structures should be of concern due to differential settlement. Giroud and Soderman [3] analyzed the tension and strain in a large-scale GM connected to long rigid structures. This work provides critical information to guide the construction of rigid structures connected to GMs. However, the problems presented by Giroud and Soderman [3] were posed as 2D plane strain problems. A solution to the three-dimensional (3D) problem is still needed.

To analyze tension and strain in a GM around a circular structure subjected to differential settlement, a simplified model based on conventional membrane theory is considered [13]. As shown in Fig.13, the surface of the medium supporting the GM is assumed to be horizontal with the GM uniformly loaded by a vertical pressure p. The GM deforms sufficiently to remain completely in contact with the circular rigid structure. Thus, the total elongation of the GM in the radial direction is equal to the differential settlement s. The tension-strain curve for the GM is assumed to be linear. The radial strain ε_r in the geomembrane can be calculated by the following equations:

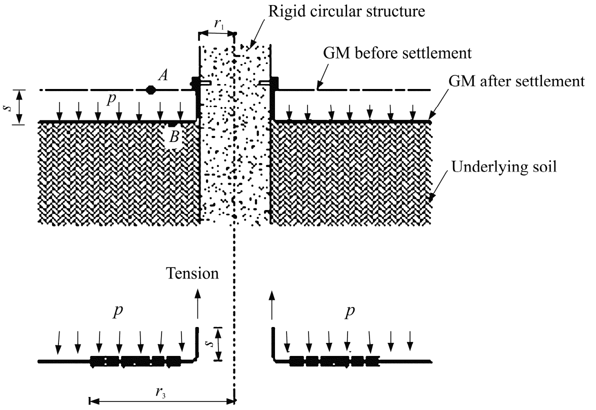

Fig.13 GM subjected to differential settlement around a circular structure.

$$\varepsilon_r = \frac{a}{6r^2}(r_3'^3 + 3r^2 r_3' - 4r'^3) \tag{9}$$

$$r_3 = \sqrt[3]{A+\sqrt{B}} + \sqrt[3]{A-\sqrt{B}} \tag{10}$$

$$a = \frac{p(\tan\varphi_1 + \tan\varphi_2)(1-\nu^2)}{E_t} \tag{11}$$

$$A = \frac{3sr_1}{a} - r_1^3 \tag{12}$$

$$B = \frac{9s^2r_1^2}{a^2} - \frac{6sr_1^4}{a} \tag{13}$$

where r' is the radial distance from the center of the GM, r_3 is the outer radius of the deformed region in the GM, r_1 is the radius of the gas venting well, φ_1 is the interface friction angle between the GM and the overlying medium, φ_2 is the interface friction angle between the GM and the underlying medium, and E_t is the tensile stiffness of the GM.

Three kinds of GMs (0.75 mm polyvinylchloride (PVC), 1 mm linear low density polyethylene (LLDPE) and 0.75 mm high density polyethylene (HDPE)) were selected for the analysis. Their tensile stiffnesses E_t are 76, 170, and 540 kN/m, respectively. The other properties used in the calculation are: $\nu = 0.45$, $r_1 = 0.5$ m, $p = 100$ kPa, $\varphi_1 = \varphi_2 = 10°$. As shown in Fig.14, the stiffness of the GM can greatly influence the maximum tensile strain ε_{max} in GMs that happens at the edges of gas venting wells. The stiffer the GM is, the smaller the ε_{max} is. The calculated ε_{max} is much larger than those calculated by the equations presented by Giroud and Soderman [3], in which a GM was connected to a rigid structure. The value of ε_{max} increases rapidly with an increase in differential settlement.

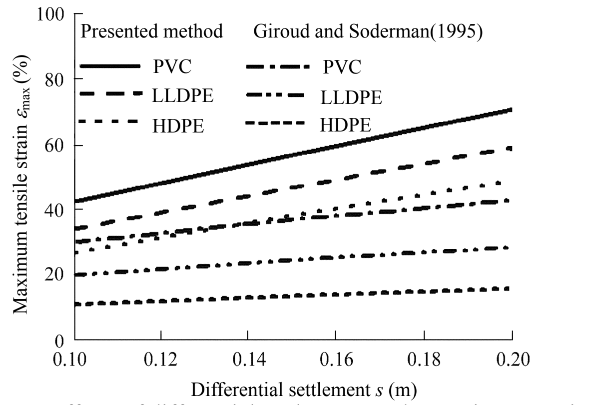

Fig.14 Effects of differential settlement on the maximum strain in GM.

3 Tensile tests and design criteria for geosynthetic liner systems

The allowable strain in geosynthetic materials ε_{allow} can be evaluated by wide-width tension tests (e.g. yield strain divided by a factor of safety). Figure 15 shows the behavior of axial tensile strength versus axial strain for some geosynthetic materials from our tests. It can be seen that the curves for the HDPE and LLDPE GMs show a pronounced yield point. According to Koerner [14], the initial response of a geosynthetic clay layer (GCL) is greatly influenced by the woven slit film geotextiles (GTs) that take the load until this component fails, and thereafter, the curve shows a distinct reduction in strength. The curve then rises gradually because the non-woven geotextile again takes the load until its ultimate failure. The tensile strength curve for the geogrid is steepest initially; however, brittle rupture happens when the axial strain is only 12%.

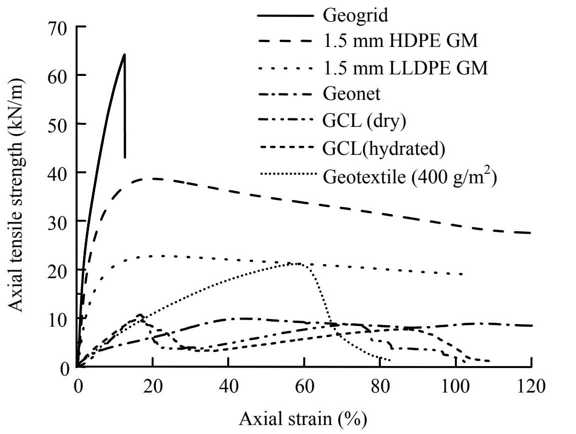

Fig.15 Tensile strength-strain behavior of geosynthetic materials.

The safe design of a landfill liner system requires that the maximum tensile strain be lower than the allowable tensile strain of the geosynthetic materials used, especially for the sealing materials such as GMs and GCLs:

$$\varepsilon_{\max} \le \varepsilon_{\text{allow}} \tag{14}$$

According to Qian et al. [5], the allowable tensile strain of a compacted clay layer (CCL) is usually less than 1%, and that of a GCL is 6%–20%. Thus, it is likely that the effectiveness of a CCL as a hydraulic barrier would not be appropriate for a vertically expanded landfill, and the GCL should be considered as an alternative. With respect to the GM component of the composite liner systems, two GMs (HDPE and LLDPE) were considered. However, HDPE has a much larger potential for stress cracking (brittle fracture under a constant stress less than the yield stress or break stress of the material) and lower allowable strain than LLDPE [15, 16]. Peggs et al. [16] presented some general guidance for the maximum allowable strains of GMs, with values ranging from 4% to 8% for HDPE and 8% to 12% for LLDPE. Thus, a textured LLDPE combined with GCL is recommended to serve as the sealing materials for the composite liner system in the Suzhou landfill.

4 Practical measures

As shown in Fig.7, the maximum tensile strain resulting from the overall settlement and lateral deformation of the existing landfill is lower than the allowable tensile strain of LLDPE and GCL. Thus, it will not cause tensile damage to the LLDPE and GCL in the proposed composite liner system. However, the inclination of the leachate drainage layer above the composite liner will be altered due to the overall settlement of the existing landfill. If the slope direction of the leachate drainage layer was reversed, a large amount of leachate would stay in the composite liner system. The potential for infiltration of the leachate into the existing landfill would increase. Thus, practical measures need to be taken, which may involve adjusting the thickness of the base backfill under the composite liner system (e.g. increasing the backfill thickness at locations where settlement is anticipated to be greater). The inclination of the leachate drainage layer should be set to at least 2% after the settlement of the existing landfill is completed.

As shown in Fig.8, geogrid reinforcement is a commonly used technique for mitigating local subsidence in an existing landfill. Measures for stabilizing existing refuse before the construction of a composite liner system can include: preloading with excess mass, deep dynamic compaction, and lime/fly ash slurry injection. Jang et al. [4] stated that placing controlled fill (soil or waste) above an existing landfill is a feasible and economical method to protect a non-reinforced liner system from the impact of local subsidence. It can provide a thick buffer or a strain-transition zone. As shown in Fig.16, the proposed composite liner system for the Suzhou landfill includes a thick bedding layer (acting as a buffer) and two layers of geogrid reinforcement, which are expected to effectively reduce the strain in the geosynthetic liners resulting from local subsidence.

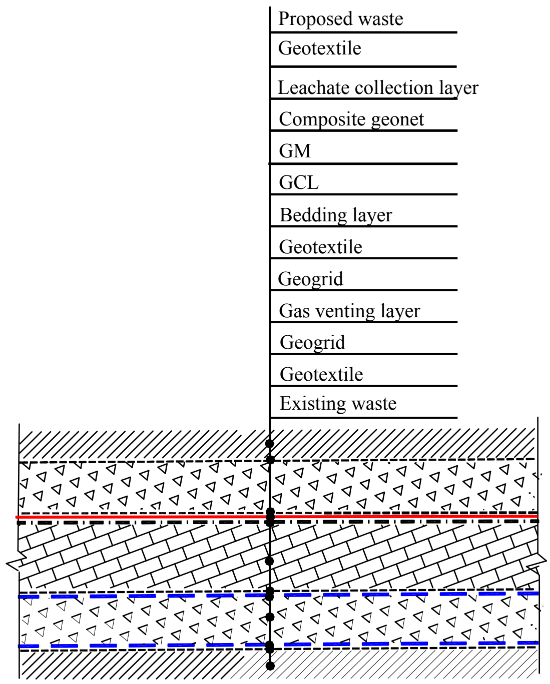

Fig.16 Illustration of the composite liner system in the Suzhou landfill expansion.

As shown in Fig.14, the calculated strain has exceeded the allowable strain of LLDPE, even when the differential settlement is only 0.1 m. Therefore, special attention needs to be paid to the behavior of the GM around the gas venting wells where differential settlements are the most significant. According to Giroud and Soderman [3], battering the walls of rigid structures was an effective solution to the problem, which created a progressive transition of settlement between the compressed medium (waste) and the structure. However, constructing a battered gas venting well may be difficult or expensive. A battered wall may also cause a load transfer from the compressed medium and conflict with the strategy to lubricate the walls of a structure to minimize load transfer as the waste settles. For these reasons, Flex connectors are recommended to connect the GM to the gas venting wells. These connections may consist of a flexible corrugated tube that can compensate for anticipated differential settlement [13].

5 Conclusions

The deformation and integrity of a composite liner under a variety of factors are important issues to be considered in landfill expansion design. Based on a case study, this paper has investigated strain in exemplary geosynthetic materials used in composite liner systems for expanded landfills, with strain resulting from both overall settlement and lateral movement of the existing landfill, local subsidence and differential settlement around gas venting wells. The following conclusions are drawn.

(1) The lateral movement of the existing landfill has a greater effect on the strain in liners than that caused by overall settlement. Significant tensile strain (about 2%) occurs near the anchor trench on the back slope and the shoulder of the front slope of the existing landfill. The tensile strain resulting from lateral movement and overall settlement of the existing landfill is not expected to induce tensile damage in the geosynthetic materials proposed for the composite liner system of the Suzhou landfill.

(2) The vertical earth pressure acting on the geosynthetic liner that is subjected to local subsidence may be larger than the Terzaghi loose earth pressure if the overlying waste is sufficiently thick. The displacement-related earth pressure is recommended for the design of a reinforced composite liner system. The use of a geogrid can reduce the tensile strain due to the local subsidence. A two-layer high-strength geogrid can usually satisfy the design requirement for the expanded landfills when the thickness of expanded masses is less than 40 m.

(3) Special attention must be paid to the behavior of the GM around gas venting wells where differential settlement can be induced with landfill expansions. Flex connectors are recommended to be used to connect the GM and the gas venting well, which can compensate the effects caused by likely differential settlement in such areas.

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